GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L14711, doi:10.1029/2005GL023469, 2005

How have soil temperatures been affected by the surface temperature and precipitation in the Eurasian continent?

Qi Hu and S. Feng

Climate and Bio-Atmospheric Sciences Group, School of Natural Resources and Department of Geosciences, University of Nebraska-Lincoln, Lincoln, Nebraska, USA

Received 11 May 2005; revised 21 June 2005; accepted 5 July 2005; published 30 July 2005.

[1] In light of the importance of soil temperatures at shallow depths as the source of the deep (terrestrial) soil temperature variations, this study examined how variations of the former have been associated with the surface air temperature (SAT) variations, testing the hypothesis that the deep soil temperatures, e.g., borehole temperatures, can be used as a proxy of the SAT. Over 153 stations in the Eurasian continent were used in the study. Its major results show a dominant SAT effect on the soil temperatures across the continent and over the seasons, but also depict precipitation influences in some regions, most significantly in winter. The latter suggests that the terrestrial soil temperatures may be more accurately considered as a proxy of very low frequency varying climate conditions at the surface. **Citation:** Hu, Q., and S. Feng (2005), How have soil temperatures been affected by the surface temperature and precipitation in the Eurasian continent?, *Geophys. Res. Lett.*, *32*, L14711, doi:10.1029/2005GL023469.

1. Introduction

[2] Surface air temperature (SAT) variations are the key indicator of regional and global climate change. Knowledge of the variations at decadal to centennial scales can assist us to anticipate and adapt to future climate and environment. Thus, gaining such knowledge has been the focus of many studies. A primary method used among them is to reconstruct SAT using proxies based on various assumptions [e.g., *Mann*, 2002; *Briffa and Osborn*, 2002; *von Storch et al.*, 2004; *Moberg et al.*, 2005]. For example, terrestrial temperatures retrieved from boreholes drilled down 200–500 meters beneath the surface were used to reconstruct SAT [*Lachenbauch and Marshall*, 1986; *Pollack et al.*, 1998; *Huang et al.*, 2000; *Beltrami and Harris*, 2001; *Beltrami*, 2002; *Beltrami and Bourlon*, 2004; *Pollack and Smerdon*, 2004]. An assumption in this reconstruction is that the SAT has been the primary source of variations in terrestrial temperatures and influences from other sources, such as geothermal fluxes, are negligible [*Lachenbauch and Marshall*, 1986; *Beltrami*, 2002]. Within the validity of this assumption, the unique damping and filtering effect of the soils allows only longer, decadal to centennial, scale and larger amplitude variations in the SAT to penetrate to greater depths and be recorded in the terrestrial temperature variations. With less interference by higher frequency variations (noise) the terrestrial temperatures have potential to capture the long timescale variations in SAT. Yet, a concern remains on the assumed relationship of the SAT and terrestrial temperature variations, arising from lacking a direct link or a "proof" showing that the SAT is indeed the primary source of the terrestrial temperature variations. In addition to the on-going observatory and modeling efforts to prove, or disprove, this link [e.g., *Putnam and Chapman*, 1996; *Baker and Ruschy*, 1993; *González-Rouco et al.*, 2003], an independent method to evaluate this link is to examine the relationship of historical SAT and available soil temperatures at shallow depths (1–5 meters). Because the shallow soil temperatures are the heat source and will propagate deep into the borehole depth over time, their relationship with SAT variations shall prove a similar association of the terrestrial temperatures and SAT.

[3] In this note, we report the results of such a study and show 1) how the soil temperatures in the first meter column at stations in the Eurasian continent were influenced by the SAT *and* by precipitation, and 2) how such influences have varied between latitudinal zones wherein precipitation and snow cover differ dramatically and between seasons in which different forms of precipitation, rain vs. snow, could affect soil temperature differently. These results will offer observational evidence of SAT and precipitation influences on the soil temperatures, and help clarify several issues in the on-going discussions of how the terrestrial temperatures reconstructed from the borehole data could represent SAT variations in historical and paleo time [e.g., *Baker and Ruschy*, 1993; *Beltrami and Kellman*, 2003; *Chapman et al.*, 2004; *Mann and Schmidt*, 2003; *Pollack and Smerdon*, 2004; *Schmidt and Mann*, 2004; *Zhang et al.*, 2001].

2. Data and Methods

[4] We obtained the monthly soil temperature data from 104 stations in Russia, 27 stations in Mongolia, and 280 stations in mainland China (total 411 stations). The Russian data were from *Barry et al.* [2001], and the Mongolian and Chinese data were from *Tang et al.* [1989, 1998]. These soil temperature data were measured at various depths in the top 1.0 m. Because most of the stations have measurements at 0.8 m for the period 1960–90, we used the 0.8 m soil temperatures in our analysis.

[5] The soil temperature variations were compared with variations in SAT and precipitation at the same or a nearby station [from *Gleason*, 2002; *Feng et al.*, 2004], which is the closest and <50 km from the soil station and has at least 240 months of concurrent observations. Of the 411 stations, 153 have "on-site" observations of SAT and precipitation. All the data from those 153 pairs of soil and surface weather stations were selected. They were normalized to remove the differences in mean and standard deviations between the soil and surface data series so that their variations can be

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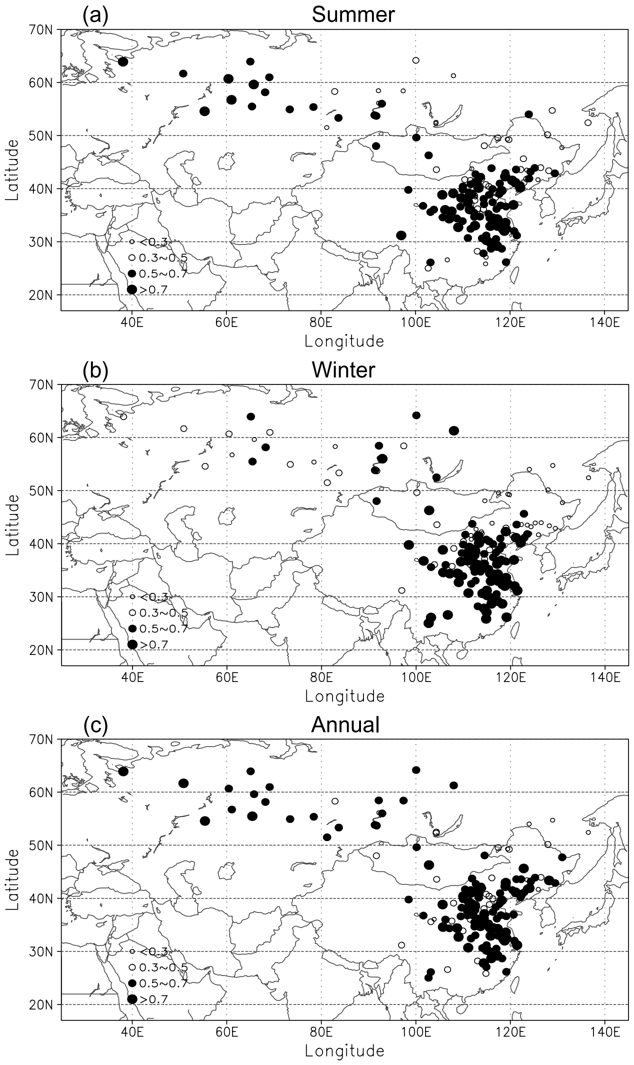

Figure 1. (a–c) Spatial distribution of the soil temperature stations and the lagged-correlation of their temperature with on-site or nearest SAT. Ranges of the correlation strength are shown by the size of the open circle and solid dot.

compared and contrasted. In addition, the average soil temperatures, SAT, and precipitation from stations in different latitudinal zones were calculated, using the "first difference method" [*Peterson et al.*, 1998], and examined to identify the latitudinal variations of SAT and precipitation effects on soil temperatures.

[6] One way to examine the influence of SAT and precipitation on the soil temperature would be to use the heat diffusion method and a best fit of "effective thermal diffusivity" derived from the surface and soil data for each station [e.g., *Putnam and Chapman*, 1996]. An alternative method is to directly examine the relationship using a statistically-derived delay factor equivalent to the fitted effective thermal diffusivity. This delay factor describes the collective effect of soil properties on soil heat diffusion and thermal inertial [*Hillel*, 1980]. This alternative is used in this study. At 0.8m depth, our analysis showed that soil temperatures at 144 of the 153 stations lagged SAT variations (the delay factor) by nearly 1 month (the largest among all the lagged correlations). Accordingly, we examine 1-month lagged-correlations of the soil temperature and SAT at the individual stations.

3. Results and Discussions

[7] Figure 1 shows the lagged-correlation of variations in the boreal summer (June, July, and August), winter (December, January, and February), and annual soil temperatures and SAT at the 153 stations (e.g., average soil temperature of July–September was correlated with average SAT of June–August). In summer, 105 of the stations show statistically significant positive lagged-correlations (solid dots indicate the confidence level at 0.05 for stations with 240 months of data and 0.01 for stations with 360 months of data). In winter, significant lagged-correlations also exist at 97 stations. When including the spring and autumn results we found the annual average soil temperatures varied closely following the SAT variation at 118 stations (Figure 1c). The 1-month lagged-variations of the annual average soil temperatures with the SAT, in various latitudinal zones, are shown in Figure 2, depicting a fairly cohesive lagged relationship between the variations in various climate zones. These very close captures of the SAT variations by the soil temperatures suggest the latter as a good proxy of the former.

[8] These results also suggest an insignificant effect of precipitation on soil temperature variations. This speculation is further examined from analyzing both 1-month lagged and simultaneous variations in the normalized soil temperature and precipitation, and the results of lagged-

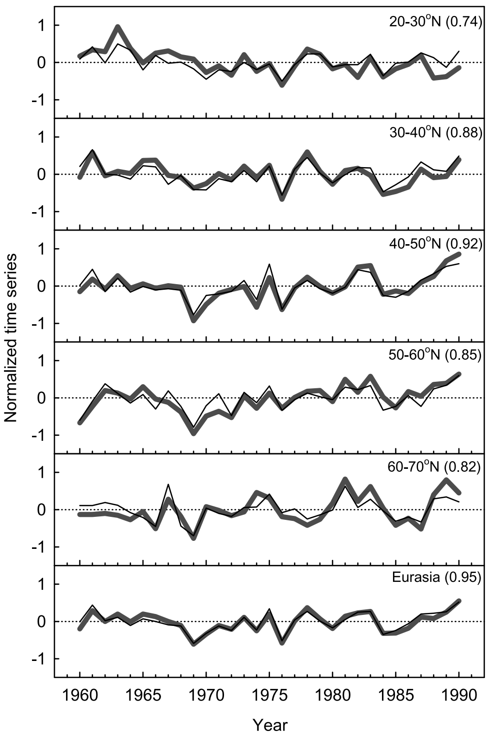

Figure 2. Temporal 1-month lagged-variations of annual average soil temperature (thick line) and SAT (thin line) in different latitudinal zones (correlation coefficient is in the parentheses). Lagged-correlation values for different seasons are given in Table 1.

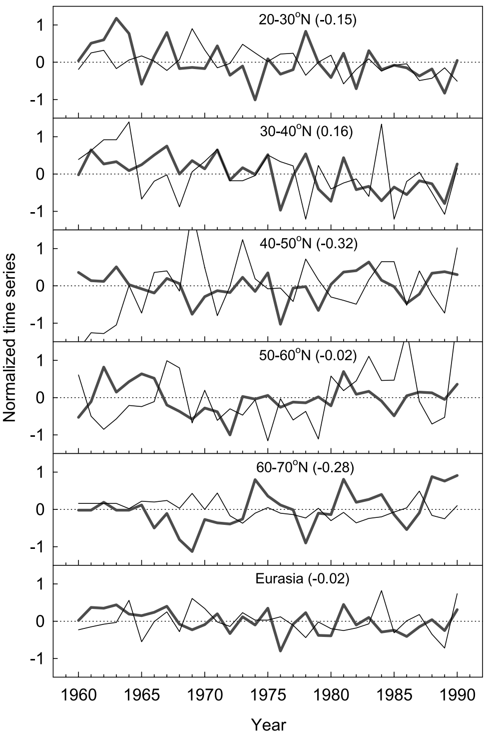

Figure 3. Temporal variations of summer season soil temperature (thick line) and precipitation (thin line) in different latitudinal zones (correlation coefficient is in the parentheses). Lagged-correlation values for other seasons are given in Table 1.

correlations for summer are shown in Figure 3 for different latitudinal zones (results from simultaneous correlation are similar). Because of the spatial distribution of the stations, these averages could represent the relationship in various climates. For example, the three zones south of the 50°N Parallel represent the humid climate in southern China and arid climate in northern China and Mongolia with a transition zone in between across central China. The two zones north of the 50°N Parallel have cold climate of different severity across Russia. Examining Figure 3, we found a general negative relationship of the soil temperature with precipitation in the warm season, a result indicating percolating rainfall cools the soil temperature. This cooling effect is weak, however, as indicated by the insignificant correlations. Similar weak effect of precipitation on soil temperature also is found in spring and autumn, as summarized in Table 1. Although the precipitation has a noticeably strong positive correlation with the soil temperatures north of the 60°N, because of winter snow insulation of cold air effect on the soil temperatures, the precipitation effect is much weaker than the SAT effect on soil temperatures, a result consistent with several recent model simulations and observations [*Lin et al.*, 2003; *Bartlett et al.*, 2004].

[9] A contrast of the precipitation and SAT relationships with the soil temperatures presented in Table 1 clearly indicates the dominant influence of SAT on the shallow soil temperatures. Through their direct connection to deep soil temperatures, the latter would be primarily affected by the SAT, particularly in the lack of other major thermal sources. The dominance of SAT on deep soil temperatures would be further enhanced by the soils' natural filtering capacity, which significantly weakens and, at greater depths, completely eliminates short timescale variations propagating downward from the surface. The deeper a signal penetrates into the soils, the longer timescale and large amplitude components in the signal would survive. Because of such capacity, the seasonal effect of winter precipitation on shallow soil temperatures would be lost before reaching to deeper depths. The relevance of this discussion to the reliability of the surface temperature reconstructed from the terrestrial temperatures is that only annual and longer timescale variations of the SAT may be preserved in great depths, e.g., boreholes, and according to the results in Table 1 (last row), only SAT variations at such timescales affect significantly the shallow soil temperatures and, hence, may be able to register at those depths. For this reason, it may be reliable to use the borehole temperatures to refer to the surface temperatures into the distant past.

4. Concluding Remarks

[10] The statistical results showing the primary effect of SAT on soil temperature variations in the first meter column across different latitudes and seasons on the Eurasian continent are consistent with those of measurement, modeling, and observational studies [e.g., *Putnam and Chapman*, 1996; *González-Rouco et al.*, 2003; *Moberg et al.*, 2005]. Moreover, results of this study provide a different perspective on the relationship of the deep soil temperature and SAT as well as precipitation, adding independent evidence supporting the hypothesis that the SAT may be inferred from the terrestrial temperatures.

[11] Meanwhile, because precipitation has also been found to influence the soil temperatures, particularly in high latitude regions and in winter season, the inferred "surface temperatures" from terrestrial temperatures could have been more accurately describing a "very low-frequency varying *surface climate condition*, " even though it may be primarily influenced by SAT. (Precipitation effect could be included or contained in the surface temperatures; for example, in a given latitude region, more precipitation would result in relatively cooler surface temperatures). The complication of such precipitation effects on the surface conditions urges caution for interpreting the retrieved surface data from borehole temperature and other proxies.

Table 1. Lagged-Correlations of Soil Temperature With SAT and Precipitation (in Parentheses) in 1960–90 (Asterisk Indicates 95% Confidence Level)

	Latitudinal Zones					
Season	20°–30°N	30°–40°N	40°–50°N	50°–60°N	60°–70°N	Eurasia
Winter	0.83*	0.89*	0.69*	0.72*	0.75*	0.89*
	(−0.14)	(0.39*)	(0.33)	(0.26)	(0.48*)	(0.45*)
Spring	0.82*	0.82*	0.86*	0.86*	0.64*	0.89*
	(−0.21)	(−0.12)	(0.22)	(0.31)	(0.21)	(0.02)
Summer	0.68*	0.84*	0.78*	0.66*	0.86*	0.84*
	(−0.15)	(−0.16)	(−0.32)	(−0.02)	(−0.28)	(−0.02)
Autumn	0.84*	0.89*	0.87*	0.67*	0.66*	0.90*
	(−0.34)	(−0.03)	(−0.33)	(0.15)	(−0.26)	(−0.09)
Annual	0.74*	0.88*	0.92*	0.85*	0.82*	0.95*
	(−0.37*)	(−0.06)	(0.00)	(0.32)	(0.06)	(0.10)

[12] **Acknowledgments.** We thank the two anonymous reviewers whose comments have helped improve this manuscript. This work was supported by funding from NOAA to the University of Nebraska-Lincoln (NA03OAR4310077) and from USDA Coop Research Project NEB-40-008 (Agricultural Research Division, University of Nebraska-Lincoln contribution number 14583).

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S. Feng and Q. Hu, Climate and Bio-Atmospheric Sciences Group, School of Natural Resources and Department of Geosciences, University of Nebraska-Lincoln, Lincoln, NE 68583-0728, USA. (qhu2@unl.edu)